The Benefits of Spin Polarization for Fusion Propulsion

G. Bruhaug[1,2] and A. Kish[1,3]

[1]Laboratory for Laser Energetics, University of Rochester
[2]Department of Mechanical Engineering, University of Rochester
[3]Department of Physics and Astronomy, University of Rochester

Nuclear fusion has long been considered an ideal method of space propulsion due to the extremely high fuel-specific energy (~2×10^6 greater than the best chemical fuels) and exhaust velocity (~4% of the speed of light versus ~4 km/s for the best chemical fuels). This high performance will allow for rapid interplanetary missions as well as interstellar missions within the lifetime of the researchers involved.[1] Fusion propulsion suffers, however, from two primary complications: the difficulty of igniting a self-sustaining fusion chain reaction and the large amount of ionizing radiation generated by the reaction, which requires a considerable mass of shielding to protect against this radiation.[1] This summary describes the ability of a unique, yet well known, nuclear physics technique known as "spin polarization" to lower both the ignition requirements and the flux of ionizing radiation that the spacecraft must handle.

All nuclei possess an inherent angular momentum known as "spin" that plays a significant role in nuclear reactions, especially nuclear fusion. Spin polarization is the process of aligning the nuclear spin vectors of the fusion reactants prior to the reaction. For five-nucleon fusion reactions, notably DT (deuterium and tritium) and D^3He (deuterium and helium-3), spin polarization serves to increase the cross section for fusion and force the reaction products to emit anisotropically. Increasing the reaction cross section lowers the requirements to reach fusion ignition, allowing the spacecraft to use less energy for ignition and requiring less total circulating power during operation. This will decrease both the fusion reactor equipment mass and radiator mass. Additionally, the anisotropic emission of reaction products allows a substantial fraction (up to 80%) of the neutron radiation to be directed away from the spacecraft, reducing the required shielding mass.[2]

Several methods for producing spin-polarized nuclei have been considered and tested for the purposes of nuclear physics experiments and producing beams of spin-polarized particles in particle colliders. For fusion reactors that require a constant stream of gaseous fusion fuel, various optical pumping techniques provide options for creating jets or beams of polarized fusion fuel. These techniques are technologically mature, but they do suffer from various polarization-loss mechanisms, e.g., contact with the walls of the fuel transport system. For fusion reactors that can operate with frozen-fuel injection, spin polarization can be achieved via super chilling of the fuel and/or the application of a strong (>10-T) magnetic field. These methods allow for pellets of prepolarized fuel to be created and stored before injection into the reactor.[2]

A limiting factor on the utility of spin-polarized fuel is the depolarization rate in the fusion reactor.[2] For rapidly pulsed fusion reactors with no significant magnetic fields, the rate of depolarization can be far slower than the expected reaction time. In long-pulse or steady-state fusion reactors, the recycling of fuel from the reactor walls can significantly deplete the population of polarized fuel. Additionally, the presence of an external magnetic field can quickly depolarize the fuel depending on the alignment of the spin polarization with the magnetic field. Such reactor analysis is beyond the scope of this summary, but the authors recommend fusion concepts such as inertial confinement fusion to capitalize on the benefits of spin polarization based on this preliminary analysis.

A unique aspect of spin-polarized DT fusion is the anisotropic emission of the neutrons and alpha particles. This emission profile, seen in Fig. 1 for neutrons, can be leveraged to significantly reduce the neutron radiation impacting the ship while also providing more propulsive efficiency due to the favorable emission profile of the alpha particles (the inverse profile of the neutrons). Figure 2 shows an artistic conception of the change in neutron emission profile on the famous VISTA inertial fusion-powered spacecraft design.

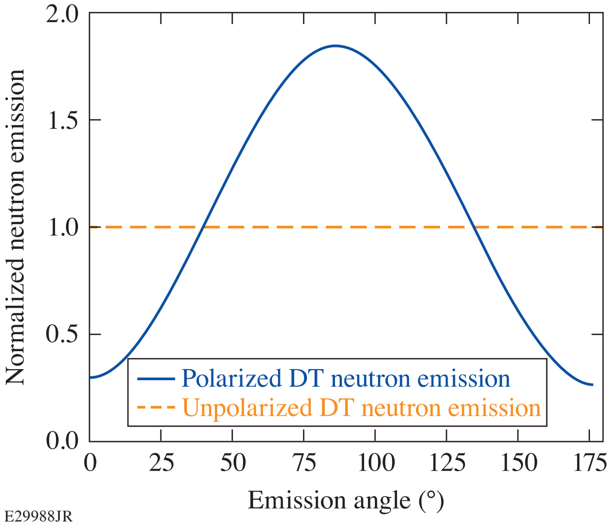

Figure 1
Neutron angular emission profile for polarized and unpolarized DT fuel in the center of mass frame.

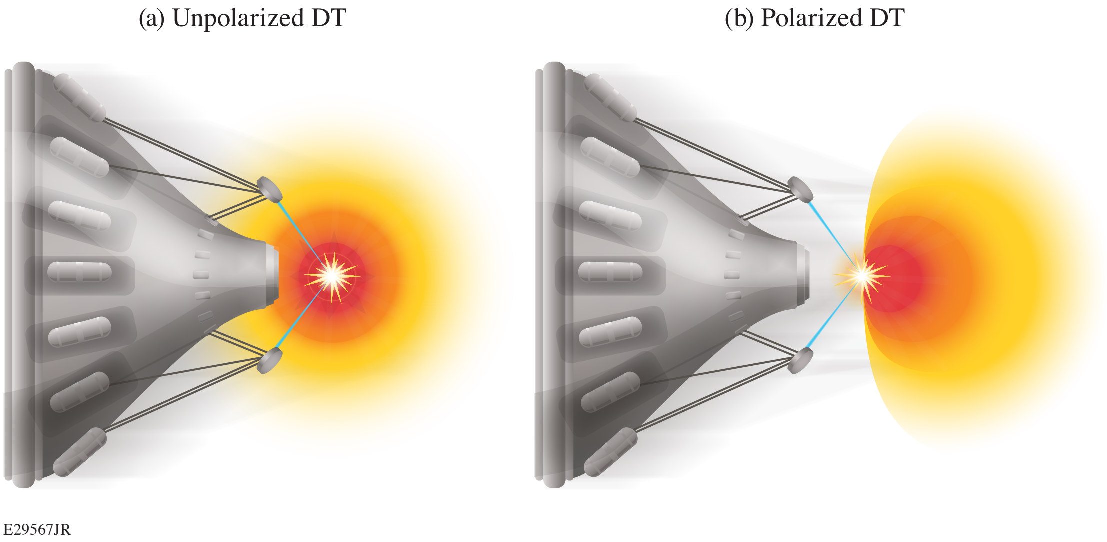

Figure 2
(a) Neutron emission profile from unpolarized DT; (b) Neutron emission from polarized DT.

A conservative analysis was performed to estimate the required radiation shielding, fusion ignition energy, and propulsive efficiency for spacecraft using both spin-polarized DT and spin-polarized D^3He fusion fuel. Based on this analysis we estimate >20% reduction in ignition requirements, ~45% more fusion burnup, ~2% reduction in radiation shielding mass, and >30% increase in propulsive efficiency of the fusion rocket. DT fusion provides the greatest benefits; polarizations >60% were found to provide less radiation flux onto the spacecraft than similarly polarized D^3He fuel. This surprising result shows the incredible potential of spin-polarized DT to act as a power source for future spacecraft.

The authors recommend that future research into fusion spacecraft consider the potential of spin-polarized fuel to improve the structure and performance of spacecraft propulsion and shielding.

1. C. D. Orth, Lawrence Livermore National Laboratory, Livermore, CA, Report UCRL-TR-110500 (2005).
2. G. Ciullo *et al.*, in *Nuclear Fusion with Polarized Fuel*, Springer Proceedings in Physics (Springer International Publishing, Switzerland, 2016), Vol. 187, pp. 1–13.